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Bond Strength in Multilayer Casting of Self-Consolidating Concrete

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Multilayer casting of self-consolidating concrete (SCC) can be critical in situations involving casting of successive lifts. The increase in structural buildup at rest of freshly cast SCC material prior to the placement of a successive layer can result in lift lines and loss in interlayer bond strength. Delay in the casting of successive lifts without mechanical consolidation can further reduce bond. Eight SCC mixtures designed to develop different levels of structural buildup at rest were investigated. The structural buildup at rest was determined by multiplying the values of initial slump flow, T50, or J-ring flow by average rates of change in these properties with rest time. Bond between successive layers was determined using composite specimens cast with two lifts of SCC after rest periods of 17 to 52 minutes, which corresponds to 25 to 60 minutes of concrete age. Bond strength was determined using the slant shear and direct shear test setups. Compared to monolithically cast samples, composite specimens had residual bond strengths of 15 to 100%. The critical delay time to secure at least a 90% residual bond strength was found to vary between 5 and 55 minutes, depending on the structural buildup at rest of the concrete in the existing layer. Statistical models for predicting residual bond strength between successive lifts were established and account for the structural buildup at rest of the first lift and delay period between successive lifts. Based on the level of structural buildup at rest, three categories of SCC are proposed. Category III SCC with relatively low structural buildup at rest can develop high residual interlayer bond. Such concrete should have maximum slump flow filling ability index of 800 mm.mm/min (31.5 in.in./min), T50 viscosity index of 0.08 sec. sec/min, and J-ring passing ability index of 600 mm.mm/min (23.6 in.in./min).

Keywords: bond strength; fold lines; lift lines; multilayer casting; rheology; self-consolidating concrete; structural buildup at rest; thixotropy.

INTRODUCTION

The construction of large concrete elements, as in raft foundation and long wall elements, necessitates the casting of multiple concrete lifts. In casting self-consolidating concrete (SCC), lack of mechanical consolidation of a lower lift prior to casting of a successive lift can lead to the formation of a distinct surface, as shown in Fig. 1, which can exhibit lower mechanical properties and impermeability than the bulk concrete layers. Such weakness in casting can increase with further delays in concrete delivery and in hot weather conditions, that can accelerate the hydration rate of cement in the already-cast lift. It is important to note that lift/fold lines are associated with the casting of concrete onto an existing concrete that is still in the plastic state that can lead to the formation of a distinct interface. This is in contrast with cold joints that occur due to the casting of concrete against a concrete surface that has already set.

Many research studies[1-5] recommend reducing the casting rate of SCC in deep vertical elements or using special mixture design approaches and admixtures to enhance concrete thixotropy and reduce formwork pressure. However, low casting rates and use of viscosity- or thixotropy-enhancing admixtures can increase the structural buildup at rest (or static yield stress) of the existing concrete, thus leading to multilayer casting of different lifts in SCC placement. Surface defects are illustrated in Fig. 1, where a fold line (or lift line) can be observed between the castings of successive lifts of SCC in a large structural wall. The selected SCC was highly thixotropic to enhance stability and reduce lateral pressure characteristics. A delay period of approximately 25 minutes occurred before the casting of the upper lift. Despite an approximately 1 m (3.28 ft) freefall in the formwork onto the existing lift, the top layer of concrete simply spread over the existing one with limited intermixing and monolithic action of the cast element across the lift line.

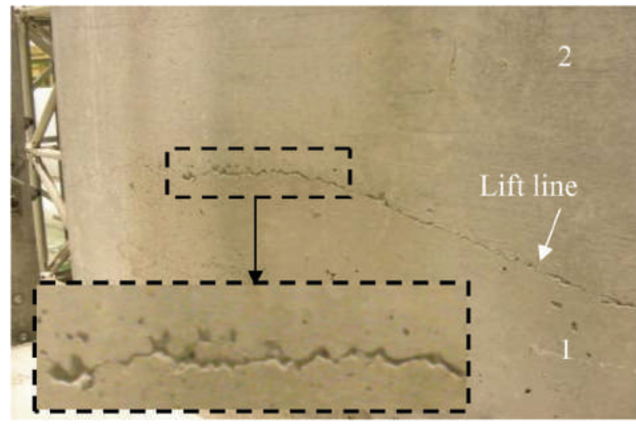

Fig. 1—Multi-layer casting of SCC in large wall element (courtesy of K. H. Khayat).

The basic mechanisms behind the effect of thixotropy on multilayer casting of SCC has been discussed by Roussel.[6] It is concluded that during placement, a layer of SCC often has a short time to rest and flocculate before a second layer of concrete is cast above it. If the fine particles can flocculate, the structural buildup of the concrete at rest increases beyond a critical value, which prevents the two layers to combine, as in the case of monolithic concrete layer. Thus, this leads to the formation of a weak interface that is sometimes described as a lift line. Losses of bond strength of more than 40% have been reported.[7] Losses of bond strength

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well over 50% have been reported when the SCC is highly thixotropic and when the elapsed time between the casting of two layers exceeds 30 minutes.[8] The drop in quality of the interface between successive lifts can also lead to a sharp increase in local permeability of the concrete.

Bond strength between two successive layers depends on the interface adhesion, friction, aggregate interlock, and time-dependent factors.[9] Friction and aggregate interlocking, in turn, depend on a number of parameters, such as aggregate size, shape, and texture.[10] Shear strength can decrease with the decrease in aggregate interlock across a bonded interface. Moreover, the volume of coarse aggregate influences the contribution of aggregate interlock to shear capacity of SCC.[11] Bond between two successive concrete layers can be improved by increasing the surface roughness of the old layer. In the case of the hardened concrete, bond to newly cast concrete can be improved by roughening the surface of existing concrete using wire-brushing, sandblasting, or other methods. In case of freshly cast SCC, after a certain period of rest, the static yield stress of the concrete can increase and reach a critical value that prevents it from intermixing with the next lift of SCC. The critical period of rest before the casting of the successive layer depends on the rheological properties of the concrete employed. The surface roughness can be improved by applying an external mechanical vibration to the existing concrete layer, which would result in reducing its yield stress. Another approach is to increase the freefall height of the new layer onto the existing material. Such vibration energy or freefall height should be adapted to avoid segregation or bleeding, which can have impaired bond between successive concrete layers. In addition to these factors, the measured bond strength is highly dependent on the test method used. The size and geometry of the specimen and the state of stress on the contact surface are quite dependent on the selected test method.

Bond strength between two concrete materials can be investigated using a number of test methods that can subject bond surfaces to direct or indirect shear, tension, or flexural stress.[10,12-17] These tests can also be used to evaluate bond strength across boundary zones in multilayer castings. In most cases, the bond surface for a direct shear test is subjected to shear stress and a small bending stress. The nature of the stress state along the bond surface and the presence of stress concentration zones can lead to scattering in test results.

Freshly cast SCC exhibits structural buildup after a certain period of rest that increases the static yield stress of the material. Structural buildup at rest can have a significant effect on the contact characteristics in multilayer castings and can be evaluated using rheometric or empirical test methods.[18] This includes the portable vane and inclined plane test methods.[19,20] The structural buildup at rest can also be evaluated using conventional test methods employed to evaluate the filling ability or passing ability of SCC; in this case, the change in workability of undisturbed samples with time of rest is evaluated. The main objective of the testing program presented in this paper is to evaluate the coupled effect of the structural buildup at rest of SCC at the delay time between the castings of successive SCC lifts on bond strength. Of special interest is the use of conventional workability test methods of SCC to assess the structural buildup at rest of SCC instead of rheometric test methods. The effect of freefall distance of a newly cast lift of SCC onto an existing lift, which can lead to intermixing of the concrete between the lifts and reducing the degree of loss in bond strength at the interface of both materials, is also investigated.

RESEARCH SIGNIFICANCE

Placement of SCC in mat foundation and large wall elements often necessitates the casting of concrete in multiple lifts that can lead to lift line formation, which could result in aesthetic defects and structural deficiencies. There is a critical need to develop recommendations to quantify bond strength across lift lines in multilayer construction and design SCC mixtures with the necessary rheological characteristics to mitigate this phenomenon. The investigation discussed herein offers guidelines to evaluate residual bond strength in multilayer casting for SCC of different thixotropic levels. Minimizing the impact of delay in casting successive SCC lifts and designing SCC with adapted rheology should be of interest to material engineers and construction planners. The conventional workability test methods can provide significant contribution to the growing demand of quantifying the structural buildup at rest of concrete, which is a challenge for quality control of SCC on jobsites.

EXPERIMENTAL WORK

Materials

Eight SCC mixtures proportioned with various materials and designed to develop different fresh and hardened characteristics were prepared. The mixture proportions and fresh properties of the investigated concrete are summarized in Table 1. The initial slump flow values ranged between 630 and 700 mm (24.8 and 27.6 in.). The majority of the mixtures were prepared with a ternary cement (CSA Type GUbS/SF) containing approximately 22% granulated blast-furnace slag, 6% silica fume, and 72% Type GU cement, by mass. Other SCC mixtures were prepared with Type GU cement. Manufactured calcium carbonate with a specific gravity of 2.7 was used in one of the SCC mixtures containing the ternary binder, thus resulting in a quaternary binder system.

Two continuously graded crushed limestone aggregates with nominal maximum sizes of 10 and 14 mm (0.39 and 0.55 in.) were used. Riverbed siliceous sand was employed. The particle-size distributions of the coarse aggregates and sand lie within CSA A23.1 recommendations. The combined coarse aggregate and sand have fineness modulus values of 6.4 and 2.5, respectively. Their bulk specific gravities are 2.71 and 2.67, respectively, and their water absorption rates are 0.38% and 0.6%, respectively.

Three types of polycarboxylate-based high-range water-reducing admixtures (HRWRAs), PCP1, PCP2, and PCP3, complying with CSA3-A266.6-M85 Specifications were used. The HRWRAs have specific gravities of 1.05. A lignosulfonate-based set-retarding admixture (SR) with a specific gravity of 1.22 was employed in some SCC mixtures. Two commonly used liquid-based types of polysaccharide-based VMAs (VMA1 and VMA2) were used.

Table 1—Mixture proportioning and fresh properties of investigated concrete

Mixture		SCC1	SCC2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8
w/*cm*		0.42	—	0.42	0.39	0.37	0.39	0.37	0.34
w/*p*		—	0.37	—	—	—	—	—	—
Ternary cement, kg/m³		475	415	—	—	—	475	475	475
GU cement, kg/m³		—	—	425	475	475	—	—	—
Limestone filler, kg/m³		—	183	—	—	—	—	—	—
S/*A* by volume		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sand (0 to 5 mm), kg/m³		783	766	816	803	844	803	803	803
Coarse aggregate, kg/m³	5 to 10 mm	810	157	—	830	173	830	830	830
	5 to 14 mm	—	628	835	—	692	—	—	—
HRWRA, L/m³	PCP1	3.25	—	—	3.35	8.0	4.0	4.96	6.7
	PCP2	—	5.0	—	—	—	—	—	—
	PCP3	—	—	5.82	—	—	—	—	—
VMA, mL/100 kg of cement	VMA1	420	—	—	—	750	—	—	580
	VMA2	—	—	220	—	—	—	—	—
SR, mL/100 kg of cement		190	—	—	190	—	190	190	100
AEA, mL/m³		—	—	—	—	—	—	—	—
Slump flow, mm		700	640	630	650	700	670	670	630
Unit weight, kg/m³		2300	2350	2330	2360	2400	2350	2330	2340
Air content, %		3.9	1.6	4.5	3.0	1.4	1.9	3.8	4.1

Notes: 1 kg/m³ = 1.686 lb/yd³; 1 mL/m³ = 26.97 oz/yd³; 1 mm = 0.03937 in.

Their specific gravities are 1.0 and 1.2, respectively. An air-entraining agent (AEA) was added to one of the mixtures.

Evaluation of workability and structural buildup at rest

The initial slump flow, T50 (ASTM C1611), and J-ring flow (ASTM C1621) values were measured 8 minutes after the initial contact of cement and water. After the initial sampling, the concrete was kept inside the mixer without any agitating with the mixer properly covered to minimize water evaporation. After 17 minutes of rest time (25 minutes of age), the concrete was sampled to determine the second set of slump flow, T50, and J-ring flow values. The molds were filled in a single layer without any consolidation. This procedure was repeated after 34 and 52 minutes of rest to measure the third and fourth sets of workability values, respectively. Three batches were prepared for each of the investigated concretes for the fabrication of the samples required for bond strength determination. In total, 24 batches were prepared.

Assessment of bond strength between successive SCC layers

Two test methods were used to investigate the effect of workability loss on residual bond strength between two successive lifts of SCC. The first method consisted of determining the bond between two layers using the slant shear test (ASTM C882). This test is widely employed to evaluate bond strength of resinous repair materials to concrete substrates and involves casting a cylindrical sample made of two identical halves bonded along a slant phase of 30 or 45 degrees from the vertical direction. The composite sample is tested under uniaxial compression. In this method, 12 cylinders with dimensions of 100 mm (3.94 in.) in diameter and 200 mm (7.87 in.) in height were cast in two layers for each mixture with the interface between the layers set at an inclination of 30 degrees from the top, as indicated in Fig. 2. For achieving this, the molds were cast at an inclined position, as shown in Fig. 2(a), and the samples had to be saw-cut to produce the required geometry. The slant shear strength was calculated by dividing the maximum load at failure by the area of the interface between successive layers, as indicated in Fig. 2(a). Such area is calculated as 0.7854 $A \times B$, where A and B refer to the maximum and minimum lengths of the elliptical cross section of the bonded zone, respectively.

The second test method involved the direct shear strength approach between successive layers. In this method, 12 cubic samples measuring 150 x 150 x 150 mm (5.91 x 5.91 x 5.91 in.) were cast for each mixture. The interface between the two concrete layers was oriented in the horizontal direction during casting and then in the vertical direction during testing, as shown in Fig. 3. The use of such direct shear specimen molds can avoid stress concentration at the edge of the bond plane, which is essential to reduce scattering of bond strength results. The fabrication of the direct shear test samples is simple and, unlike the slant shear test, it does not require saw-cutting the sample before testing.

In both testing methods, a delay time between the casting of the first and the second layers was set to 15, 30, 45, and 60 minutes. The second layer of SCC consisted of concrete that was properly mixed without any rest, which would represent actual concrete practice. The SCC in the

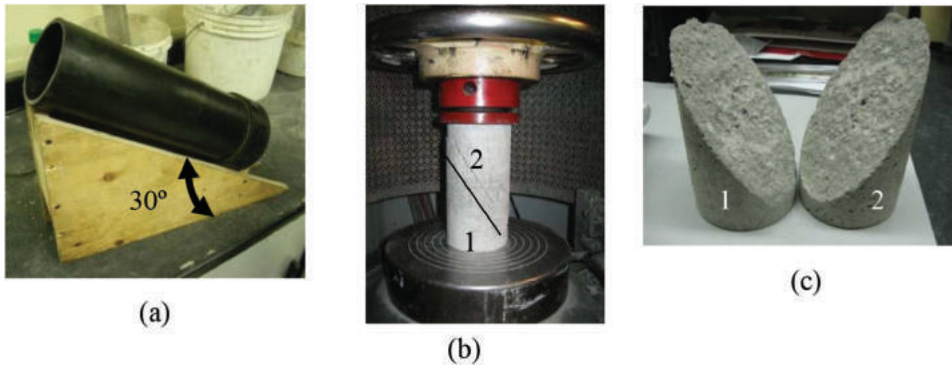

Fig. 2—Slant shear strength: (a) casting; (b) sample under testing; and (c) failure pattern.

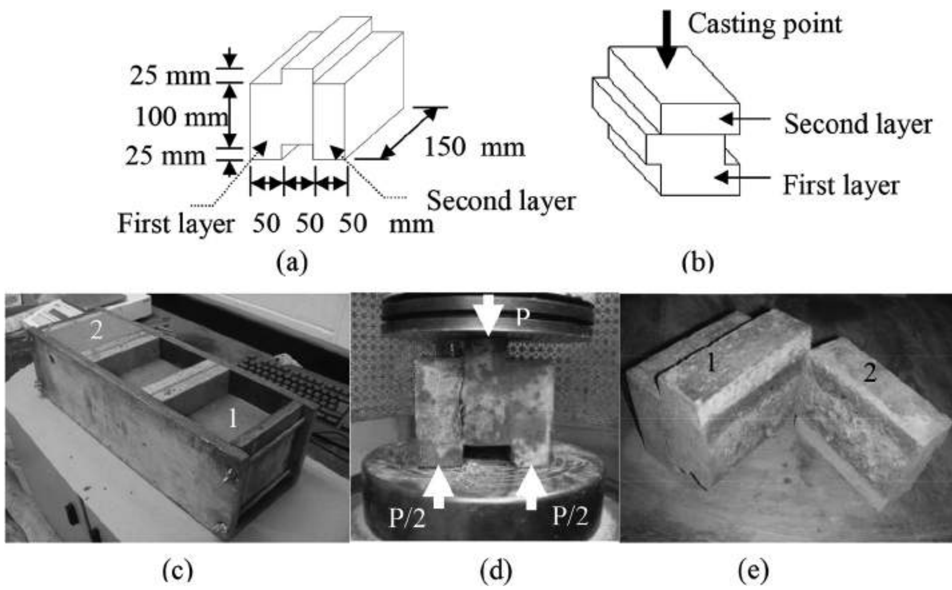

Fig. 3—Direct shear strength: (a) dimensions; (b) mold arrangement; (c) casting; (d) sample under testing; and (e) failure pattern. (Note: 1 mm = 0.03937 in.)

second lift was allowed to drop a short height of 50 mm (1.97 in.) above the existing concrete upper surface. Three samples per testing condition were cast to determine average bond strength values. Another three samples were cast in one layer to secure monolithic conditions and are considered as control samples. For the direct shear test method, an additional cube was cast using SCC1 where the second layer was placed after 60 minutes with initial freefall height of 300 mm.

After 7 days of moist curing, all samples were tested under compression (Fig. 2(b) and Fig. 3(d)) with the load gradually applied at 0.15 to 0.35 MPa/s. The failure mode and appearance of the slant shear and direct shear strength tests were noted, as shown in Fig. 2(c) and Fig. 3(e), respectively.

EXPERIMENTAL RESULTS AND DISCUSSION

Structural buildup at rest

The values of the slump flow, T50, and J-ring flow determined after rest periods of 0, 17, 34, and 52 minutes are summarized in Table 2, Table 3, and Table 4, respectively. The reported properties are average values of three sets of measurements carried out on the three batches required for casting the bond strength samples. The results were used to determine various indexes to evaluate the degree of structural buildup at rest of the concrete. The filling ability index (FAI) was calculated by multiplying the initial slump flow value ($S.flow_{(0)}$) by the average rate of loss in slump flow at rest time ($R_{s.flow}$) between 0 and 52 minutes. The normalized FAI values reported in Table 2 varied between 340 mm.mm/min (13.4 in.in./min) for SCC1, which has lowest thixotropy, to 2110 mm.mm/min (83.1 in.in./min) for SCC8, which has the highest thixotropy. The viscosity index (VI) was calculated by multiplying the initial T50 value ($T50_{(0)}$) by the average rate of increase of T50 with rest time (R_{T50}), which is considered as the viscosity structural buildup at rest index. VI results reported in Table 2 ranged from 0.03 sec.sec/min for SCC1 of thixotropy to 5.37 sec.sec/min for the highly thixotropic SCC8 mixture. Finally, a passing ability index (PAI) was calculated by multiplying the initial J-ring flow ($J\text{-}ring_{(0)}$) by the average rate of drop in J-ring flow with rest time ($R_{J\text{-}ring}$). The PAI values, reported in Table 2, varied between 415 mm.mm/min (16.3 in.in./min) for SCC1 to 1910 mm.mm/min (75.2 in.in./min) for SCC8.

Residual bond strength across boundary of successive layers

The slant shear strength and direct shear strength results are given in Table 3. The relative slant shear strength and

Table 2—Variations of slump flow, T50, and J-ring flow with rest time and rates of changes in workability with rest time

Mixture	SCC1	SCC2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8
	Slump flow results							
Slump flow at t* = 0 min	695	640	630	650	705	665	665	630
Slump flow at t = 17 min	690	630	600	620	675	625	625	570
Slump flow at t = 34 min	680	615	570	590	645	590	585	515
Slump flow at t = 52 min	670	605	540	560	610	550	545	455
Rate of slump at flow drop, $R_{s\text{-}flow}$, mm/min	0.49	0.69	1.73	1.73	1.82	2.2	2.31	3.35
Filling ability index, FAI, $S.flow_{(0)} \times R_{s\text{-}flow}$, mm.mm/min	340	440	1090	1125	1285	1465	1535	2110
	T50 results							
T50 at t* = 0 min	1.11	1.51	1.65	1.79	2.05	3.45	4.43	7.78
T50 at t = 17 min	1.59	2.06	2.74	3.08	3.51	5.06	8.00	19.38
T50 at t = 34 min	2.07	2.61	3.83	4.37	4.98	6.67	11.57	31.11
T50 at t = 52 min	2.58	3.19	4.99	5.73	6.54	8.38	15.35	—
Rate of increase in T50, R_{T50}, sec/min	0.03	0.03	0.06	0.08	0.09	0.10	0.21	0.69
Viscosity index, VI, $T50_{(0)} \times R_{T50}$, sec.sec/min	0.03	0.05	0.10	0.14	0.18	0.35	0.93	5.37
	J-ring flow results							
J-ring flow at t* = 0 min	715	630	590	640	685	660	645	580
J-ring flow at t = 17 min	705	610	565	620	660	635	610	525
J-ring flow at t = 34 min	695	590	545	595	635	605	575	465
J-ring flow at t = 52 min	685	570	520	570	610	580	540	410
Rate of J-ring flow drop, $R_{J\text{-}ring}$, mm/min	0.58	1.16	1.33	1.36	1.45	1.56	2.02	3.29
Passing ability index, PAI, $J\text{-}ring_{(0)} \times R_{J\text{-}ring}$, mm.mm/min	415	730	785	870	995	1030	1305	1910

*t is rest time; 1 mm = 0.03937 in.

Table 3—Slant shear and direct shear strength results

Mixture		SCC1	SCC2	SCC3	SCC4	SCC5	SCC6	SCC7	SCC8
Slant shear strength, MPa	t* = 0 min (control samples)	44.3	42.9	39.9	52.2	49.8	52.9	51.4	55.1
	t = 15 min	43.3	41.8	38.8	50.5	47.9	49.4	47.0	49.0
	t = 30 min	42.3	40.8	37.7	48.8	46.0	45.9	42.6	42.9
	t = 45 min	41.3	39.7	36.6	47.0	44.2	42.4	38.2	36.8
	t = 60 min	40.3	38.7	35.5	45.3	42.3	38.9	33.8	30.7
	Reduction rate in strength, 10^2 MPa/min	6.7	7.0	7.3	11.5	12.5	23.3	29.3	40.7
Direct shear strength, MPa	t = 0 min (control samples)	10.3	8.9	8.4	10.3	11.9	10.8	11.8	12.2
	t = 15 min	9.7	8.2	7.6	9.2	10.7	9.3	9.7	9.6
	t = 30 min	9.1	7.5	6.9	8.1	9.2	7.6	7.8	7.0
	t = 45 min	8.4	6.9	6.1	7.1	7.9	5.9	6.0	4.4
	t = 60 min	7.8	6.2	5.3	6.0	6.6	4.2	4.1	1.8
	Reduction rate in strength, 10^2 MPa/min	4.2	4.5	5.1	7.1	8.9	11.1	12.7	17.3

*t is rest time; 1 MPa = 145 psi.

direct shear strength values are calculated by dividing the individual results obtained after various periods of rest by the corresponding values obtained for the control samples cast monolithically in a single layer. These values were used to evaluate the residual bond strength, expressed in percent, which can be developed between successive layers.

The variations of residual bond strength for the slant shear test (RB_{SSh}) and direct shear stress test (RB_{DSh}) of the investigated SCC mixtures cast with delay time (DT) between the castings of successive lifts are plotted in Fig. 4 and Fig. 5, respectively. The results show that both residual bond strength test values decrease with the increase in DT. SCC1 designed to develop the lowest level of structural buildup

Table 4—Effect of structural buildup at rest and delay time on residual bond strength

SCC category		I	II	III	I	II	III
Bond test method		Slant shear strength			Direct shear strength		
Structural buildup at rest		High	Moderate	Low	High	Moderate	Low
Residual bond level		Low	Moderate	High	Low	Moderate	High
FAI, mm.mm/min		≥1800	800 to 1800	≤800	≥1800	800 to 1800	≤800
VI, sec.sec/min		≥3.00	0.08 to 3.00	≤0.08	≥3.00	0.08 to 3.00	≤0.08
PAI, mm.mm/min		≥1600	600 to 1600	≤600	≥1600	600 to 1600	≤600
Residual bond strength, %	DT = 15 min	≤91	96 to 92	≥97	≤82	91 to 83	≥92
	DT = 30 min	≤83	94 to 84	≥95	≤64	82 to 65	≥83
	DT = 45 min	≤74	91 to 75	≥92	≤47	74 to 48	≥75
	DT = 60 min	≤66	88 to 67	≥89	≤29	65-30	≥66

Note: 1 mm = 0.03937 in.

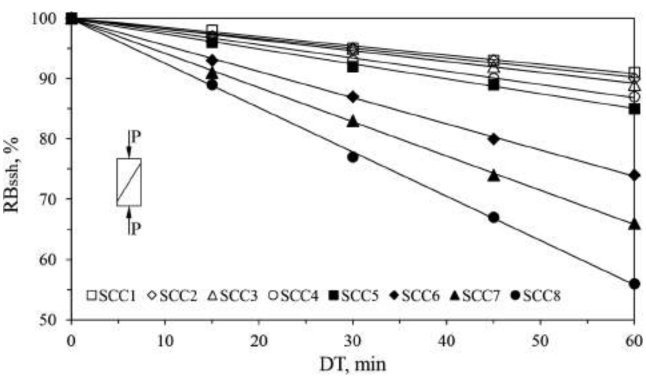

Fig. 4—Variations in residual bond strength under slant shear strength with delay time of various SCC mixtures (40 data sets).

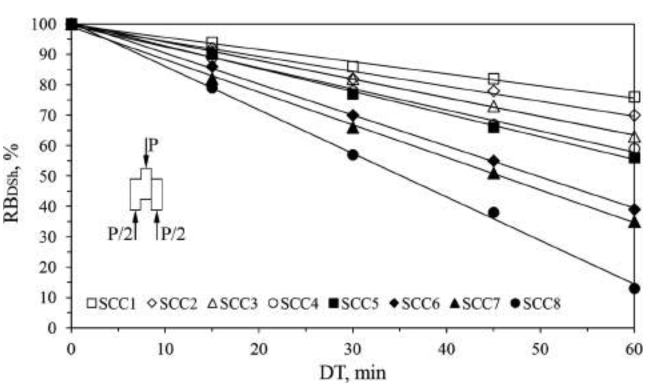

Fig. 5—Variations in residual bond strength under direct shear stress with delay time of various SCC mixtures (40 data sets).

at rest exhibited RB_{SSh} and RB_{DSh} values of 91% and 76%, respectively, after 60 minutes of age, or 52 minutes of rest time. On the other hand, the variation of such residual bond strengths dropped drastically to 56% and 15% for the SCC8 mixture that had the highest structural buildup at rest level.

The effect of increasing the degree of the structural buildup at rest of the lower SCC lift prior to casting of the upper lift on the RB_{SSh} and RB_{DSh} values is illustrated in Fig. 6 and Fig. 7, respectively. The structural buildup at rest is expressed using the filing ability structural buildup

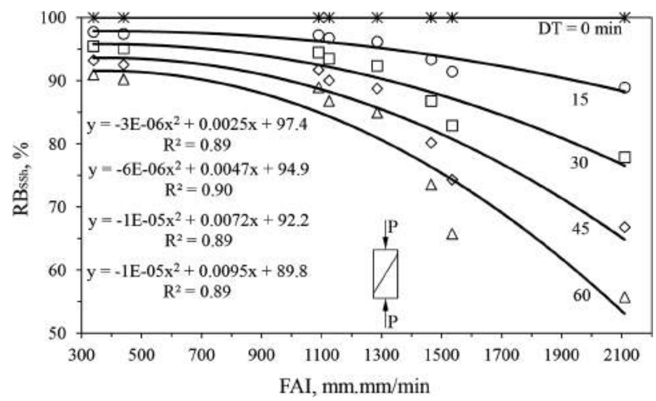

Fig. 6—Variations in residual bond strength under slant shear strength with structural buildup at rest determined using FAI and delay time (40 data sets). (Note: 1 mm = 0.03937 in.)

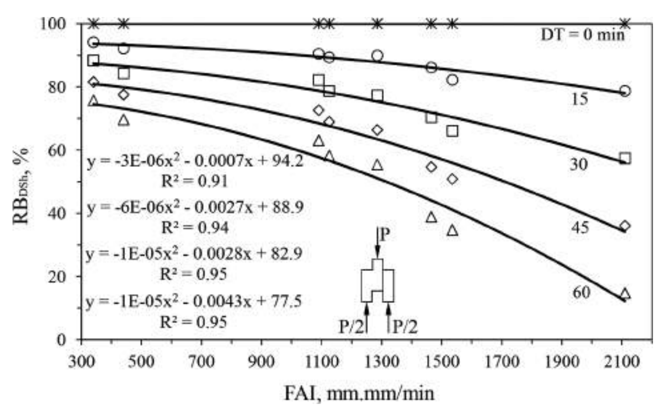

Fig. 7—Variations in residual bond strength under direct shear stress with structural buildup at rest determined using FAI and delay time (40 data sets). (Note: 1 mm = 0.03937 in.)

index (FAI). Similar trends can be established using the VI or PAI approaches. The loss of bond strength is determined for each of the eight SCC mixtures cast and five DT values. Samples cast monolithically are considered as the control samples. For a relatively short DT of 15 minutes between the castings of the two successive lifts, the RB_{SSh} and RB_{DSh} values for SCC1 were 98% and 94%, respectively. On the other hand, for a DT of 60 minutes, the RB_{SSh} and RB_{DSh}

values for SCC8 that had the highest FAI value were 56% and 15%, respectively. The residual strength determined by the direct shear strength test was more sensitive to defects that can exist at the distinct layer between the two SCC lifts than the slant shear strength.

Given the performance of the residual bond strength that varies with the bond strength test method, or the orientation of the interface at the boundary between adjacent lifts, the degree of structural buildup at rest of the lower lift prior to casting of a successive lift, and DT between successive lifts, SCC mixtures can be classified into three categories.

As indicated in Table 4, SCC mixtures belonging to Category I are expected to yield relatively low residual bond strength in the multicasting situation, such as in the case of SCC8. The FAI, VI, and PAI values of SCC mixtures belonging to Category I can be greater or equal to 1800 mm.mm/min (70.9 in.in./min), 3.00 sec.sec/min, and 1600 mm.mm/min (63.0 in.in./min), respectively. On the other hand, SCC mixtures belonging to Category III, such as SCC1, are expected to secure high residual bond strengths with FAI, VI, and PAI values less or equal to 800 mm.mm/min (31.5 in.in./min), 0.08 sec.sec/min, and 600 mm.mm/min (23.6 in.in./min), respectively. SCC belonging to Category II, such as SCC4 and SCC5 mixtures, have FAI values ranging between 800 and 1800 mm.mm/min (31.5 and 70.9 in.in./min), VI values between 0.08 and 3.00 sec.sec/min, and PAI values between 600 and 1600 mm.mm/min (23.6 and 63.0 in.in./min) can be designated as mixtures that can lead to moderate residual bond strength in multi-layer casting.

Category III concrete is recommended for casting elements of large dimensions or those where a certain delay prior to casting successive layers is expected. Such SCC can have a minimum initial slump flow of 630 mm (24.8 in.) and maximum rate of loss in slump flow at rest of 1.20 mm/min (0.047 in./min). Such concrete can exhibit low viscosity with an initial T50 of 1.60 sec less or equal and a rate of increase in T50 at rest less or equal to 0.047 sec/min as well as a minimum initial J-ring flow of 630 mm (24.8 in.) with a rate of drop in J-ring flow values at rest of 0.85 mm/min (0.033 in.) or less. When the delay time between castings of successive layers of SCC belonging to Category III is 15 minutes, the minimum residual bond strength determined under slant and direct shear stress can be 97% and 92%, respectively, as indicated in Table 4. These values decrease to 95% and 83%, respectively, when the DT increases from 15 to 30 minutes. Therefore, the use of concrete with workability characteristics belonging to Category III (low thixotropy) can develop a residual bond strength greater than 90% when the delay time between successive layers does not exceed 15 minutes.

Category I concrete exhibits high rate of structure buildup at rest and can have an initial slump flow less or equal to 650 mm (25.6 in.) with a sharp rate of slump flow loss of 2.85 mm/min (0.11 in./min) or more. Such concrete can exhibit very high viscosity with an initial T50 value greater or equal to 6.1 sec and a rate of increase in T50 values of 0.45 sec/min or more. Category I SCC can develop an initial J-ring flow of 615 mm (24.2 in.) or lower with a rate of drop in J-ring flow values at rest greater or equal to 2.65 mm/min (0.10 in./min). The use of SCC with such workability characteristics can develop a

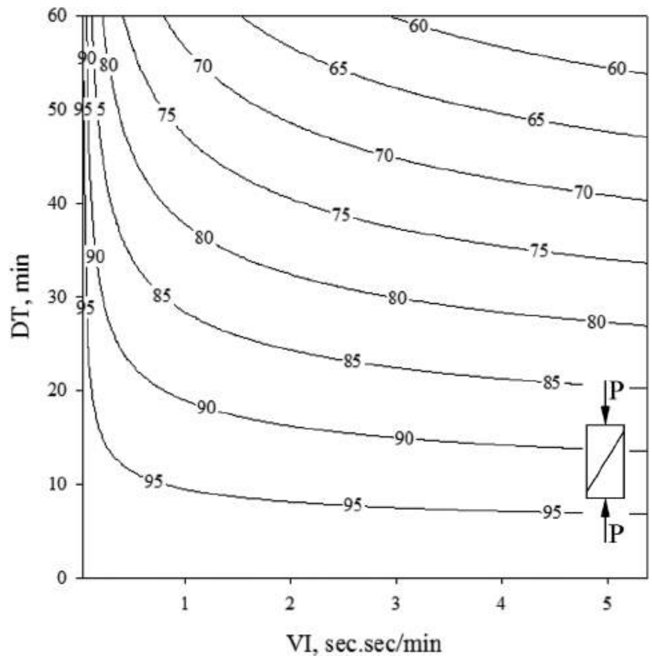

Fig. 8—Contour diagrams of variations in residual bond strength under slant shear strength with structural buildup at rest determined using VI and delay time.

maximum residual bond strength in multi-layer casting on the order of 80% if the delay time between successive layers does not exceed 15 minutes.

Models to predict residual bond strength

Equations (1) and (2) present models to estimate residual bond strength between two successive layers tested using the slant shear and direct shear strength (RB_{SSh} and RB_{DSh}) tests, respectively. The estimated residual bond strength takes into consideration the delay time (DT) between successive layers and the structural buildup at rest of the existing concrete evaluated by the T50 test, or viscosity index (VI).

$$RB_{SSh}\ (\%) = 100 - 0.53\ DT - 0.13\ DT\ Ln\ VI \quad (1)$$

$$RB_{DSh}\ (\%) = 100 - 1.11\ DT - 0.20\ DT\ Ln\ VI \quad (2)$$

where RB_{SSh} is the residual bond strength between successive layers under slant shear strength, in percent; RB_{DSh} is the residual bond strength between successive layers under direct shear stress, in percent; DT is the delay time between successive layers, in min; and VI is the structural buildup at rest evaluated by the T50 viscosity index, in sec.sec/min.

Similar models to estimate RB_{SSh} and RB_{DSh} can be established using the FAI and PAI structural buildup at rest indexes. Contour diagrams representing the models expressed in Eq. (1) and (2) are plotted in Fig. 8 and Fig. 9, respectively. To secure a residual bond strength of 90%, the critical delay time (DT_C) between castings successive lifts of SCC can be calculated using Eq. (3) and (4).

$$DT_C\ (\text{min}) = 3744 - 37.44\ RB_{SSh}\% + (4.92\ RB_{SSh}\% - 492)\ Ln\ PAI \quad (3)$$

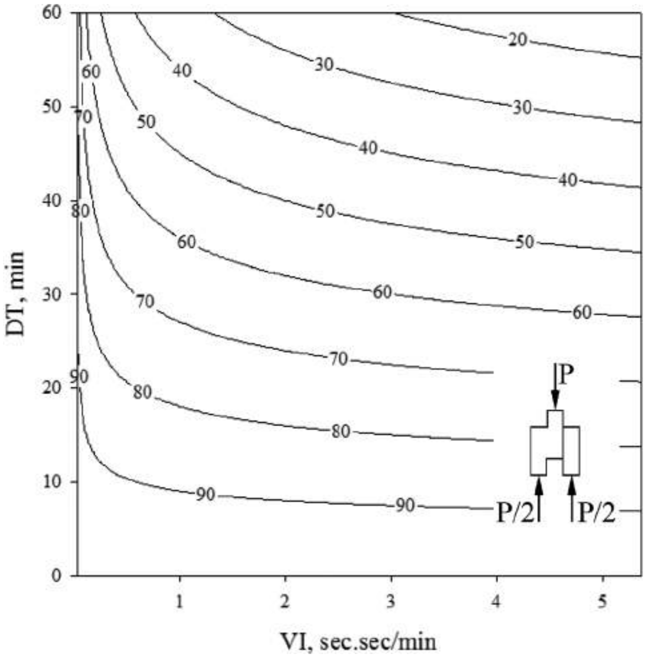

Fig. 9—Contour diagrams of variations in residual bond strength under direct shear stress with structural buildup at rest determined using FAI and delay time.

$$DT_C \text{ (min)} = 1072 - 10.72\, RB_{DSh}\% + (1.36\, RB_{DSh}\% - 136) \text{ Ln } PAI \quad (4)$$

where DT_C is the critical delay time to secure 90% residual bond strength, in min; and PAI is the structural buildup at rest evaluated by the J-ring passing ability index, in mm.mm/min.

The variations of DT_C corresponding to a residual bond strength of 90% with the PAI are plotted in Fig. 10. The DT_C between successive SCC layers is shown to decrease with the increase in structural buildup at rest of the freshly cast concrete. The DT_C determined under slant shear strength is higher than that the direct shear bond strength for SCC of a given thixotropic level. The difference between DT_C values determined using the slant and direct shear stress test methods is found to be approximately 55 minutes when concrete belonging to Category III SCC (low structural buildup at rest) is used. However, when the SCC is highly thixotropic, belonging to Category I, the spread in DT_C should decrease considerably to secure adequate bond strength.

Effect of free-fall height on bond strength

For casting molds to determine bond between two adjacent layers using the direct push-off shear strength test method, the second lift was cast onto the existing one from a very small freefall height (FFH) of 50 mm (1.97 in.) to a value of 300 mm (11.81 in.). The increase in FFH of SCC1 resulted in an increase in the RB_{DSh} from 76% to 86% when the top layer was cast after a DT of 60 minutes. The increase in bond strength with FFH can be related to an increase in the level of aggregate interlock resulting from greater surface roughness at the interface with the lower concrete lift. Figures 11(a) and (b) show photos of such interface of concrete subjected to FFH of 50 and 300 mm (1.97 and 11.81 in.), respectively.

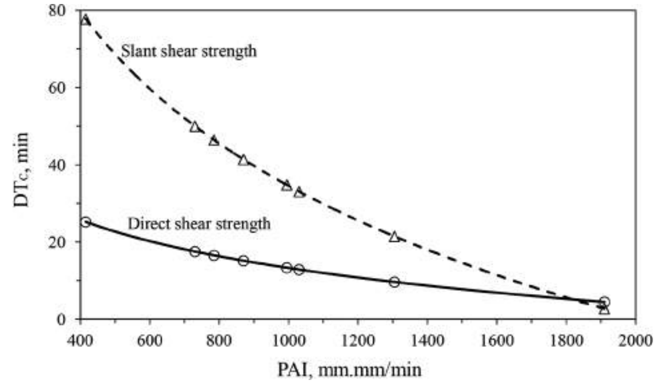

Fig. 10—Variations in critical delay time needed to achieve residual bond strength of 90% with structural buildup at rest (16 data sets). (Note: 1 mm = 0.03937 in.)

The photos were taken of sheared surfaces at the conclusion of the direct push-off shear tests. The surface roughness is shown to increase with the increase in FFH where interlock resulting from the penetration of the top concrete layer into the existing layer was obtained.

The penetration area was determined using software and is expressed as a percentage of the total area of the image. The images were displayed in grayscale, then converted into binary images following the adjustment of the background illumination to be uniform. The penetration area of the successive layer into the existing layer of concrete at the time of casting of the second lift is represented by the area occupied by the black color in Fig. 11(c) and (d), which correspond to the images shown in Fig. 11(a) and (b), respectively. The results indicate that the area occupied by the black color in Fig. 11(c) and (d) were 13% and 67%, respectively. Greater increase in FFH is expected to enhance the residual bond strength in multilayer casting of SCC, which is important for mixtures belonging to Categories I and II and those where relatively long delay periods between casting the next lift are expected. In increasing the FFH, it is important to ensure that the concrete maintains adequate resistance to dynamic segregation.

CONCLUSIONS

Based on the results presented herein, the following conclusions can be drawn:

1. The flow of SCC over freshly cast lift of concrete without any mechanical consolidation of the existing material can lead to the formation of a distinctive layer, or fold/lift line, with reduced bond across the interface.

2. Bond strength determined using the direct shear stress is more adversely affected by multilayer casting than that evaluated using the slant shear strength.

3. Depending on the degree of structural buildup at rest of an existing lift of SCC, bond strength with the successive lift can range from 80 to 95% when determined using the slant shear strength test and 55 to 90% for the direct shear stress for delay time of 30 minutes.

4. The structural buildup at rest of SCC can be evaluated by determining the variation in filling ability using slump flow test (FAI), J-ring passing ability (PAI), and T50 (VI) of undisturbed samples with rest time over 1 hour.

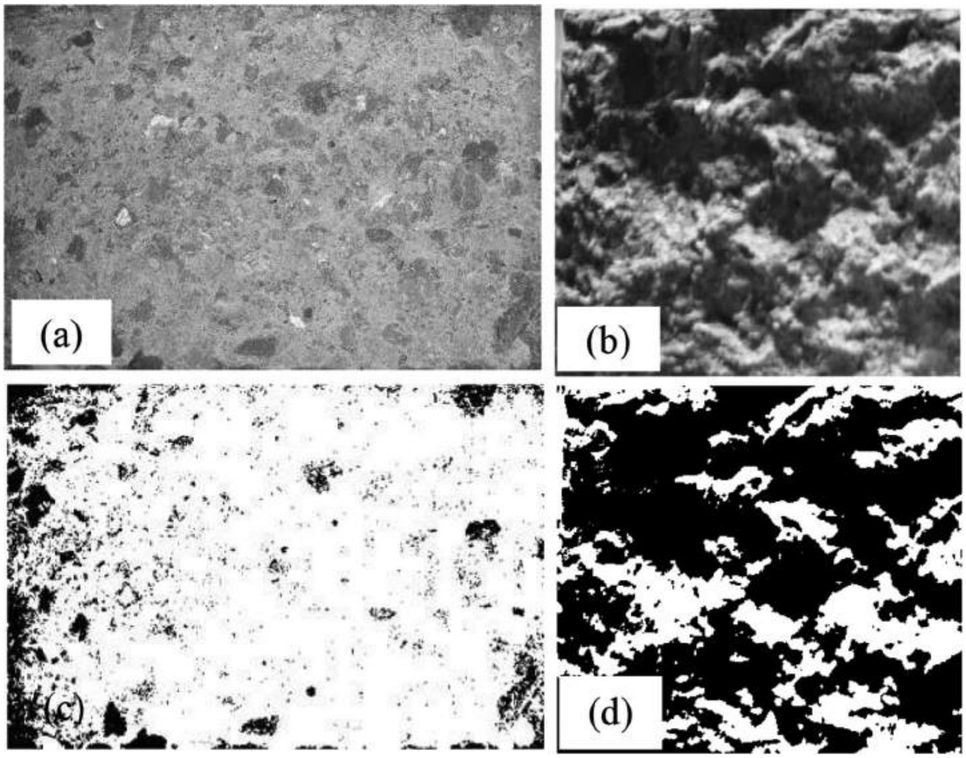

Fig. 11—Variant surface roughness at multi-casting bonded area with freefall height of SCC: (a) and (c) 50 mm (1.97 in.); and (b) and (d) 300 mm (11.8 in.)

5. Bond strength in multilayer castings of SCC decreases with the increase in structural buildup at rest of the existing SCC. The spread between the critical delay time needed to secure 90% residual slant shear and direct shear bond strengths can range from 5 to 55 minutes for SCC with relatively high and low levels of structural buildup at rest, respectively.

6. Relationships are proposed to evaluate residual bond strength using the slant shear strength and direct shear strength tests as functions of delay time between successive layers and structural buildup at rest evaluated by standard workability test methods. Similar correlations are proposed to evaluate the critical delay time required to secure 90% residual bond strength.

7. Three categories for SCC are proposed based on structural buildup at rest. Category III SCC of relatively low level of structural buildup at rest can secure high residual interlayer bond and should have maximum FAI, VI, and PAI values of 800 mm.mm/min (31.5 in.in./min), 0.08 sec.sec/min, and 600 mm.mm/min (23.6 in.in./min), respectively. Such concrete can have initial slump flow greater or equal to 630 mm (24.8 in.), a rate of slump flow drop limited to 1.20 mm/min (0.047 in./mm), an initial T50 less or equal to 1.6 sec, and a maximum rate of increase in T50 (VI) of 0.045 sec/min.

8. Moderate bond strength can be expected for SCC belonging to Category II with FAI ranging between 800 and 1800 mm.mm/min (31.5 and 70.9 in.in./min), VI of 0.08 to 3.00 sec.sec/min, and PAI of 600 to 1600 mm.mm/min (23.6 to 63.0 in.in./min).

9. Bond strength between successive layers can increase with freefall drop of the top layer above freshly cast SCC due to increase in surface roughness and interlock across the boundary. An increase in direct shear strength of 10% can be secured for Category III SCC when the freefall height increases from 50 to 300 mm (1.97 to 11.81 in.).

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